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Solar Radiation Measurement in Northern Arizona

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Radiation on clear days averaged about 78% of the extra-terrestrial value. Mean monthly radiation varied from 57% in July to 75% in June. The mean radiation for the 2-year period was 67% of extra-terrestrial. Daily radiation varied from 24 langleys for a day in January to 836 for a day in June; January mean radiation was 272 langleys/day, while the June mean was 736. Measured transmissivity is related to hours of sunshine, but the relation is not close enough for precise daily predictions.

Keywords: Solar radiation.

Introduction

Solar energy is the driving force of all the natural processes going on around us. At a given point above the earth's atmosphere, insolation on a horizontal surface (extra-terrestrial radiation) can be predicted, given latitude, date, and time. Indeed, a number of people have presented calculations and some have written computer programs to do this (Buffo et al. 1972, Frank and Lee 1966, Furnival et al. 1969, McCullough and Porter 1971). The calculations are based primarily on computations of Milankovitch (1930). A solar constant — that is, intensity of solar radiation outside the earth's atmosphere, normal to the sun's beam at the mean distance of the earth from the sun — has been developed by the Smithsonian Institution and others (List 1963). A value of 1.94 langleys/min is generally assumed. This value, equivalent to 1.353 kilowatts/m^2, has recently been confirmed from satellites and high-altitude aircraft (Duffie and Bechman 1976).

Actual radiation received at the ground varies with atmospheric conditions, however. Fairly predictable factors include Rayleigh, aerosol, and ozone distributions (Elterman 1968). The greatest — and most unpredictable — factor, however, is atmospheric moisture, which can exclude nearly all incoming infrared radiation. Whether solar energy is used by forests, range plants, irrigated agriculture, or by man for heating, knowledge of day-to-day fluctuations is important to the management of these uses. Handy and Durrenberger (1976) measured solar radiation and sunshine data received at 21 locations in the Southwest, including 8 in Arizona. Our data, for a location 20 miles south of Flagstaff, supplement those of Handy and Durrenberger.

Instrumentation

Sensing units were mounted on a horizontal platform on a 10-m tower in a forest clearing 20 miles due south of Flagstaff to measure short-wave solar radiation (0.2 to 2.5 micron (μ) wave lengths). The data are to be used primarily in various aspects of forest ecosystem modeling.

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The solar radiation we measure represents the combined direct-beam and diffuse components of the incoming radiant energy received at the forest canopy level, on a horizontal surface. It is reported in units of langleys (gram-cal/cm^2)/day (Delinger 1976), and is interpreted in respect to extra-terrestrial radiation received outside the atmosphere, and in respect to possible sunshine.[2]

Two systems were used for collecting the data. The first was an Eppley model 50 pyranometer (also known as a Kimball and Hobbs pyrheliometer). The signal from the pyranometer was transmitted to an analog stripchart recorder. The area under the analog curve was digitized on an hourly basis, and from these figures daily totals were obtained.

The second system consisted of a Kipp CM-5 solarimeter (a Moll-Gorczynski type pyranometer) connected to a Lintronic digital volt-time integrator. This instrument printed hourly integrated values on paper tape. Both sensing instruments were calibrated according to the 1956 international pyrheliometer scale.

The glass instrument domes are transparent to the lower limit of ultraviolet radiation received at the earth's surface, which is about 0.29 μ, through the visible spectrum (0.4 to 0.7 μ) and into the infrared wavelengths. However, they are not transparent to the longer infrared rays beyond 2.8 μ or 3.0 μ. Because of this upper limitation, the instruments are said to be sensitive to short-wave solar radiation. Radiometers with plastic coverings instead of glass are transparent to the longer infrared wavelengths as well.

Because the Kipp unit, installed in late 1974, had been most recently calibrated, and the two sensors differed slightly in response, all readings from the Eppley were corrected to aline with the Kipp. The correction consisted of comparing daily readings from the two systems from February through September 1975. The resulting straight-line regression equation was $\widehat{K} = 1.040E - 0.926$, where K is the Kipp reading and E is the Eppley reading in langleys/day. The regression coefficient (r) was 0.984.

Radiation Measured

The values in table 1 are mean daily corrected Eppley readings for January 1974 through January 1975, and direct Kipp readings for February 1975 through December 1975.

Radiation during December and January averaged slightly over 270 langleys/day; the low was 24 langleys. June radiation reached a high of 836, while the average for the month was 736 langleys/day.

Radiation on clear days averaged about 78% of the extra-terrestrial value. Mean monthly radiation varied from about 57% of extra-terrestrial in July to 75% in June. The mean radiation for the 2-year period was 66% of extra-terrestrial.

A plot of average daily total measured radiation (lower curve, fig. 1) for each month of the year shows a sharp dip for July due to frequent summer cloudiness. Cloudiness in March was less pronounced. Daily total radiation measured on selected clear days and average daily extra-terrestrial radiation are also shown.

The measured clear-day values, which were lower than those of Buffo et al. (1972) and Davis (personal communication), declined from about 80% of extra-terrestrial in early 1974 to about 77% in 1975. This decline probably reflects drift

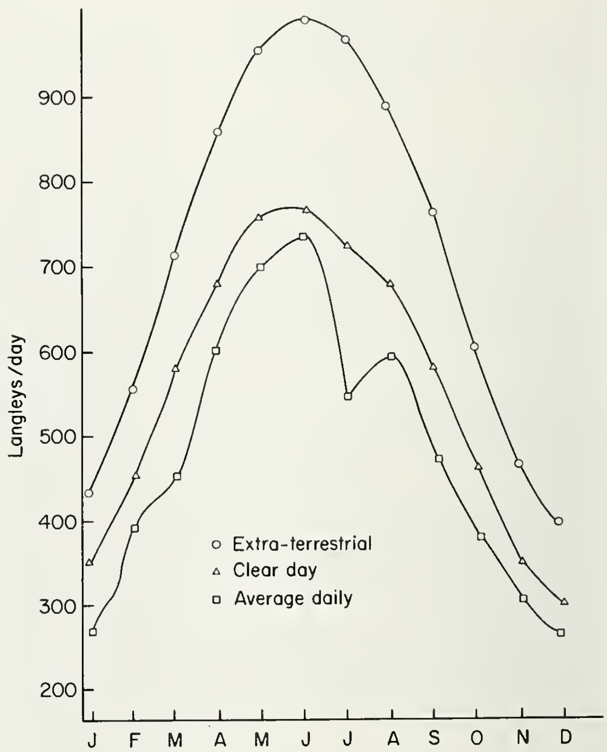

Figure 1.—Average daily extra-terrestrial, and measured clear-cay and average-day solar radiation on a horizontal surface by months near Flagstaff, Arizona. Points are average for 1974 and 1975.

[2]Some convenient conversions of langleys to other commonly used units of energy are:

100 langleys (gram-cal/cm^2)
= 368.5 BTU/ft^2
= 971.6 watt hr/yd^2
= 4.184×10^6 joule/m^2
= 1.162 kilowatt hr/m^2

Table 1.—Daily total short-wave solar radiation received on a horizontal surface in langleys. Site 34°55" N latitude, 11°38' W longitude, elevation 1,977 meters (6,485 ft.), 37 kilometers (20 mi) south of Flagstaff, Arizona. Values are average for 1974 and 1975.

Day	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						Langleys						
1	82	401	486	366	714	765	723	544	521	520	248	269
2	162	360	372	524	728	741	624	556	518	520	264	316
3	344	374	498	664	750	737	497	532	366	408	284	304
4	236	318	462	682	683	698	494	523	375	512	379	232
5	222	326	412	662	618	734	565	494	572	504	354	246
6	176	406	367	524	628	754	580	623	316	290	388	294
7	180	385	460	401	706	720	405	618	324	348	372	294
8	98	435	191	482	742	758	566	521	553	416	250	314
9	169	332	259	560	743	743	730	586	471	494	374	313
10	204	314	164	480	762	790	688	623	570	454	363	313
11	298	438	334	522	758	761	587	604	600	492	378	304
12	286	394	460	476	758	680	476	634	507	263	354	224
13	300	215	405	672	732	709	520	698	420	378	350	188
14	350	304	354	669	764	740	481	626	548	482	328	298
15	352	258	526	666	742	716	462	604	526	479	353	286
16	306	294	560	652	590	750	517	614	511	470	350	310
17	238	254	590	518	456	755	554	660	406	462	259	300
18	322	443	566	575	662	660	561	628	378	432	280	298
19	350	466	487	725	678	745	556	630	404	342	350	300
20	232	484	271	699	694	760	527	548	433	304	310	230
21	246	378	576	690	598	764	614	641	562	338	340	159
22	382	486	328	634	612	690	611	600	552	229	252	304
23	365	480	574	611	654	742	508	616	523	382	348	235
24	376	510	602	467	772	744	620	579	391	428	336	320
25	375	472	446	564	776	708	498	594	511	408	320	248
26	308	498	384	634	726	763	528	516	466	320	316	213
27	305	412	582	741	762	764	343	516	503	327	216	275
28	348	474	618	743	724	728	586	642	544	212	194	251
29	386	—	618	744	740	722	485	645	472	280	242	260
30	222	—	590	738	702	750	507	645	464	292	332	314
31	320	—	621	—	780	—	621	604	—	212	—	239
Total	8,540	10,911	14,163	18,085	21,754	22,091	17,034	18,464	14,307	11,998	9,484	8,451
Mean	275	390	457	603	702	736	549	596	477	387	316	273
Std. Dev.	85	82	130	107	72	29	84	50	78	97	54	42

in sensitivity of the sensing units, and will be verified by a future calibration check.

In terms of energy received on a horizontal surface, the average daily input is about 8.5 kilowatt hrs/m^2 in June. Using flat plate collectors sloped toward the south with a slope about equal to the latitude, the average daily radiation would be somewhat greater. Even though the solar energy intensity is low, if the energy is collected from a large surface the quantities may be large. Duffie and Buckman (1976) estimate the energy incident daily on a 200-m^2 (239 yd^2) house roof in Madison, Wisconsin, is equivalent to that obtainable from about 25 gallons of oil.

Transmissivity/Sunshine

The transmissivity, T, of the atmosphere, expressed as the ratio of total daily radiation to daily extra-terrestrial radiation, was related to the percent of minutes of possible sunshine, S. The S values were those reported by the National Weather Service (USEDS 1974, 1975) at the Flagstaff airport, 15 miles north of the radiation observation site. The daily paired values were grouped by months with the 2 years pooled, and the regression equation $\hat{T} = a + bS$ was calculated. The T value is somewhat synonymous to the Q/Q_0 of Fritz and MacDonald (1949); but T will be lower since the Q_0 value was radiation received on a clear day rather than extra-terrestrial radiation. Even though considerable month-to-month variation was evident in the regressions, all the correlation coefficients were statistically significant at the 1% level (table 2).

If percent sunshine is high, the transmissivity can be estimated rather closely. When $S = 100$, the T value of the 12 regressions was 77.8% with

a 95% confidence interval of ± 2.2%. The extremes were 71.7% and 83.7%, a span of 12%. However, when S = 0 the average T value was 8.6% ± 5.4%. The extremes were greater; 1.4% to 31.9%, a span of 30.5%.

There are two reasons why the relation between transmissivity and percent sunshine is not closer. The first is that the percent sunshine is an off-on measurement. As a cloud of sufficient density moves between the sun and the sensor, a thermally activated switch stops the timer. However, the radiometer continues to measure radiation at a reduced level in inverse proportion to the cloud density. On the other hand, high, thin clouds do not switch off the sunshine timing meter, but measured solar radiation declines somewhat.

The second reason is that cloud cover patterns may differ slightly between the radiation measuring site and the airport 15 miles away where the sunshine is timed. The correlation coefficients were slightly higher for the winter months when cloud patterns tend to be regional, than during the summer when cloud patterns are more localized.

An examination of the monthly mean transmissivity in relation to monthly mean sunshine produced a regression of $\hat{T} = 29.74 + 0.448$ S, and a correlation coefficient of 0.683. With a larger sample and sensing units closer together, a coefficient more in line with that of Fritz and MacDonald (1949) might be expected.

Table 2.—Values of a and b in the regression T = a + bS, and correlation coefficient (r), pooled for 2 years of solar radiation measurements near Flagstaff, Arizona.

Month	Regression constants a	Regression constants b	Correlation coefficient r[1]
Jan.	14.91	0.688	0.906
Feb.	14.63	0.670	0.796
Mar.	14.60	0.640	0.741
Apr.	6.86	0.754	0.831
May	1.40	0.775	0.697
June	31.89	0.455	0.731
July	15.28	0.564	0.761
Aug.	15.75	0.594	0.783
Sept.	14.51	0.606	0.785
Oct.	7.48	0.677	0.928
Nov.	17.13	0.616	0.923
Dec.	29.50	0.463	0.667

[1]Corrected average r = 0.815

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